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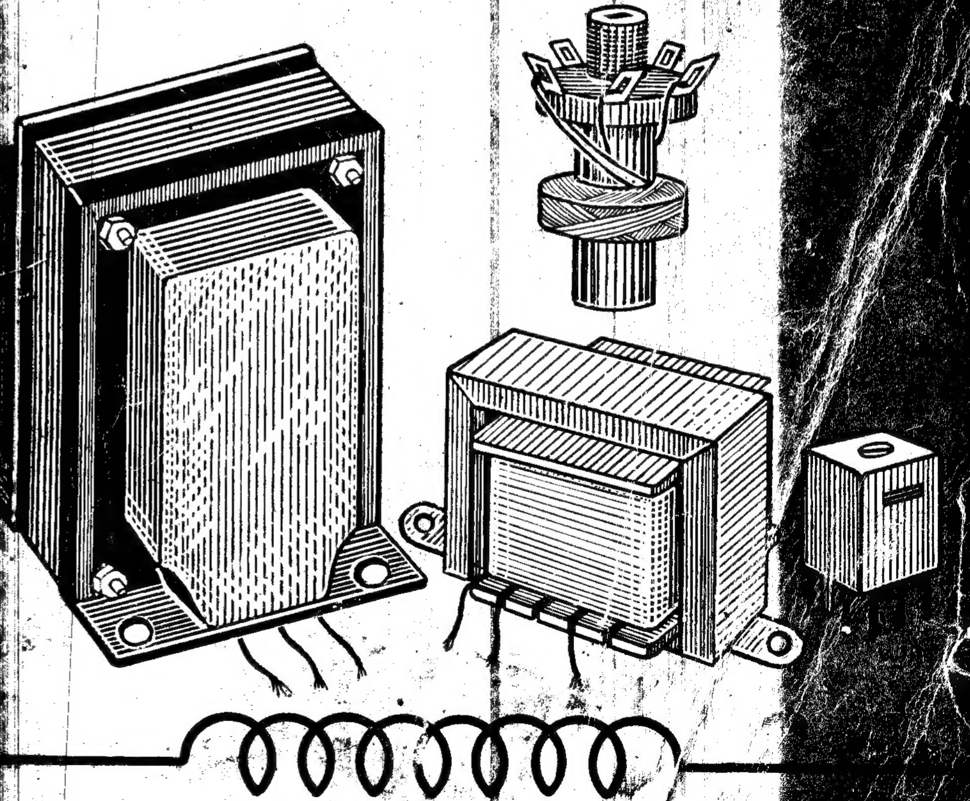
BUILD YOUR OWN COILS AND TRANSFORMERS



BUSINESS PROMOTION BUREAU

BUILD YOUR OWN COILS AND TRANSFORMERS

R. DAS

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1

Introduction

Modern technology is advancing fast. In electronics, research is going on to replace the use of coils and transformers by various devices. For instance, a few decades back it was unthinkable to use resistors as loads in RF circuits; but now special film-type resistors are manufactured which can be used at these frequencies as well without any risk of the RF currents being shunted by stray (invisible) capacities formed across these resistors at these frequencies.

Also, special integrated circuits are available which, by employing an ingenious technique, have sought to dispense with the use of coils and transformers. This ingeneous technique is called 'Phase-Locked Loop' system, and is finding use in FM transmitters and receivers. The 'Phase-Locked Loop' (PLL) system does not use coils or transformers, except in its power supply circuit. One such system is IC 567. But the operation of the PLL System is at present limited to about 500 KHZ only, (maximum).

In addition, several RC oscillators have become popular, whose frequencies are determined by the charge and discharge of capacitors through resistors. But here again the design of such oscillators is limited to about 500 KHZ. Thus, it will be a long time before the use of coils and transformers can be entirely dispensed with in electronic circuits. The chief reasons for the continual efforts being made to discard the use of coils and transformers as far as possible are : firstly, their precise design becomes unpredictable due to such factors as leakage inductance, distributed capacitances etc. Secondly, these devices are highly frequency-sensitive, that is, they tend to discriminate one frequency against another.

So, coils and transformers are going to stay with us for many more years to come. It is, therefore, necessary for personnel working in the field of electronics to become acquainted with the various techniques involved in the design, construction and operation of transformers and coils.

Let us begin at the beginning.

2. Attributes of Coils and Transformers

At the outset, we have to grasp the significance of the chief attributes of coils and transformers. These are summarized, in Table 1.

TABLE I

Attribute	*Symbol*	*Unit of Measurement*
1. Inductance	L	Henry
2. Mutual Inductance	M	Henry
3. Reactance	XL or XC	Ohms
4. Impedance	Z	Ohms
5. Resonance	Nil	Nil
6. Coil Efficiency	Q	Nil

We recapitulate below certain well-known facts of electricity and magnetism.

2.1. Whenever an electric current flows in a conductor, a magnetic field is produced. This field is in the form of concentric circles around the conductor.

2.2. Whenever the lines of magnetic field (denoted by 'Flux') are cut or intercepted by a conductor, an electromotive force (emf measured in volts or its multiples/sub-multiples) is induced in the conductor. The magnitude of the induced emf is proportional to the rate of cutting of the magnetic lines of force by the conductor (Faraday's Laws). (This is also the generator principle).

2.3. The rate of cutting of the magnetic lines of force by a conductor (known as "flux-linkage") is directly proportional to :

the rapidity of change of the current with respect to time, or alternatively, the rapidity of the movement of the conductor in the magnetic field with respect to time.

2.4. Whenever the magnitude of a current or voltage changes with respect to time we call it an alternating current or voltage (AC). Thus. the effect of the "flux-linkages" mentioned in the foregoing para is to produce an alternating emf in the conductor.

Frequencies

2.5. The variation of the current or voltage from zero, to a maximum positive, through zero, to maximum negative, and back to zero, is termed a sinusoidal "cycle". The number of cycles traversed by the current or voltage in one second is known as its "frequency". Frequency is, therefore, measured in "Cycles per second" or "Hertz".

The frequency of alternating currents or voltages may vary from a fraction of 1HZ to thousands of HZ (Zero frequency, of course, means direct current or dc).

The frequencies of AC have been classified into various categories depending upon certain special properties exhibited by them, as the frequencies increase. The frequencies are classified as shown in Table II.

TABLE II

Frequency Range	*Classification*
10 to 30 Hz	Very Low Frequencies (VLF)
30 to 300 Hz	Low Frequencies (LF)
300 Hz to 3MHZ (See foot note)	Medium Frequencies (MF)
3 MHZ to 30 MHZ	High Frequencies (HF)
30 MHZ to 300 MHZ	Very High Frequencies (VHF)
300 MHZ to 3000 MHZ	Ultra High Frequencies (UHF)
3000 MHZ to 30,000 MHZ	Super High Frequencies (SHF)

Note : MHZ denotes Mega Hertz i.e. 10^6 HZ. Similarly, KHZ denotes Kilo Hertz i.e. 10^3 HZ.

2.6. *Wavelength :* The velocity of AC i.e. the speed with which it moves is given by :

3×10^8 meters per second. This means that in one second the alternating current/emf travels 3×10^8 meters.

Frequency denotes the number of cycles per second. The inverse of the frequency of the AC is known as its wavelength and is denoted by the Greek letter λ (pronounced Lamda).

Thus, wavelength multiplied by the frequency of AC gives its speed i.e. $\lambda F = 3 \times 10^8$ meters per second

$$\text{or } F = \frac{3 \times 10^8}{\lambda} \text{ HZ per second} \qquad \text{.......... (1)}$$

$$\text{or } \lambda = \frac{3 \times 10^8}{F} \text{ Meter} \qquad \text{..........(2)}$$

The relationship between frequency and wavelength of AC is given in Table III to facilitate quick reference.

2.7 Phase : When there exists a time interval in the starting point of two alternating currents or voltages we say that there exists a phase difference between the two AC wave forms. The phase difference is measured either (a) in seconds or its submultiples such as milli or microseconds or (b) in their angular velocities indicated by degrees or radians.

We shall adopt method (b) to denote phase difference between two wave-forms. The phase difference of 90° between two sinusoidal wave forms is of particular importance. It means that one wave form attains its maximum value 90° ahead of the other. We, then, say that the first waveform is "leading" over the second waveform by 90°. We could express the same effect by saying that the second wave-form is "lagging" behind the first waveform by 90°. In simple words, all that it means is that when the value of the second waveform is zero, the first wave form has already reached its maximum value.

3. We are now in a position to appreciate what was indicated in para 2.3 above, namely, that magnetic "flux-linkages,, are directly proportional to frequency of the AC flowing through the conductor.

Now, the flux-linkages induce an emf in the conductor. The nature of this induced emf is to oppose the rise and fall of the input alternating current (LENZ'S Law). Let us visualise what actually takes place. As the source of the applied emf tries to force a current through the conductor, the induced emf opposes the rise of the current to its maximum value; that is, because of the induced emf the current flowing through the conductor reaches its maximum value much later than it would, had there been no induced emf. Similarly, when the current tends to decrease to zero, the induced emf tends to keep the current flowing through the conductor. Thus, we say that the conductor shows the property of electrical "inertia" when AC passes through it. This property of the conductor when AC is applied to it is known as its "inductance" denoted by the letter L. Mathematically induced emf= $-$ L di/dt. The minus sign indicates the induced emf acts in oppostion to the applied emf.

3.1 So far we have considered a single straight conductor or wire. Now, if the wire is bent around to form what is known as a "coil" the effects indicated in succeeding paragraphs will be observed.

As current flows through the coil, the magnetic lines in one turn of the coil cuts the adjacent turns of the same coil The net effect is that the amount of emf induced in the coil is much more than that of a straight conductor. Thus, the inductane of a coil depends on its geometrical property i.e. it depends on the shape and arrangement of its various parts and the consequent distribution of the lines of magnetic flux.

If the coil consists. of 10 turns some of the magnetic lines will cut the maximum area of all the 10 turns; whereas the other lines progressively cut less and less number and areas of the turns of the coil.

Further, the magnetic lines complete their paths through air, thereby their strength is much reduced. In addition, there will be a large number of lines which will just pass into the surrounding air without cutting a single line of force. The cumulative effect

is that the strength of the induced emf will be much reduced. We shall return to this point when we consider "cores" in Chapter II.

3.2 "SKIN EFFECT" : USE OF LITZ WIRE.

It is found that even the true "ohmic resistance" of a conductor to alternating current is not constant, but increases with frequency. This is due to the fact that when an ac flows in a conductor, the distribuution of current over the cross-section of the conductor is not uniform. The greater part of the alternating current flows along the outer parts or surface of the conductor than in the central parts. The uneven distribution of current is caused by more emf being induced in the central part of the conductor than in its surface. The induced emf, as we have seen, opposes the flow of current (Lenzs Law).

This uneven distribution of current leads to the power dissipation in the conductor being increased, and so to increase in its resistance.

This tendency of alternating currents to flow in the outer parts or "skin" of a conductor is called "skin effect", which increases with frequency. At radio frequencies practically all the current flows along the "skin" i.e. the outer surface of the conductor.

When the conductor is wound as a coil, the non-uniformity of distribution of current i.e. the "skin effect" is still more marked than when it is straight. Also, the greater the number of turns in the winding, the more pronounced is the skin effect.

The phenomenun of skin effect has led to the discovery of "Litz" wire. This wire consists of several strands which are insulated from each other and interwoven so that each strand has the same part of its total length on the surface of the resulting cable, and therefore the same proportion in the interior of the cable, as the others, thereby ensuring a much more uniform distribution of current over the cable, and a corresponding decrease in skin effect.

Litz wires are generally used in winding coils on the medium wavelengths (500 KHZ to 1 MHZ) since more number of turns of wire are required on this wave-band than on short waves.

3.3. Mutual Inductance

through one coil, the magnetic lines thus produced cut the windings of the second coil, they are said to be mutually coupled. As the magnetic lines cut the turns of second coil, they induce an emf in the second coil.

Let two coils X and Y be placed close to each other. Coil Y is supposed to be on open circuit for the time being. In Coil X let a current be maintained by a source of AC EMF. It will be found that a number of the flux produced by the current in coil X link with coil Y, this number depending on :

1. the magnitude and frequency of the current flowing in coil X
2. the shape and size of coil X
3. the shape and size of coil Y
4. the positions of coil X and coil Y relative to each other.
5. if air occupies the space intervening the two coils many of the flux will be lost in the air and the induced emf in coil Y will be weak.

The direction of the induced EMF in coil Y will be such that if current were to flow in that coil, it would act in opposition to the flux in coil X (again Lenz's Law). Thus, the induced EMF in coil Y causes an electrical "inertia" which is called "Mutual inductance".

3.4. Definitions

(1) Inductance : A coil has an inductance of one henry if the EMF induced in it is one volt when the current is changing at the rate of one ampere per second.

(2) Mutual Inductance ; Two coils have a mutual inductance of one henry if the EMF induced in one of them is one volt when the current is changing at the rate of one ampere per second in the other.

Sub-multiples of henry, frequently used in electronic circuits are milli-henry (one thousandth. $1/10^3$, of a henry) and micro-henry (one millionth. $1/10^6$ of a hentry). One milli-henry is denoted as MH and one micro-hentry as μH.

The phenomenon of mutual inductance is the basis of the 'TRANSFORMER' which we shall consider in detail at a later stage.

Summary. We have so far considered certain aspects of alternating currents and also the first two attributes (namely inductance and mutual inductance) of a coil or transformer shown in Table I.

We shall now discuss the other attributes of coils and transformers indicated in Table 1.

4. Reactance :

Reactance is the opposition presented by a pure coil or a capacitor to the flow of alternating current through it. A "pure" coil or capacitor is one without any resistance in it. The opposition offered by a resistor to the flow of current is termed as resistance. Resistance dissipates energy in the form of heat. Reactance diminishes current by setting up an opposing EMF and therefore controls a source of alternating EMF without wastage of electrical energy.

4.1. Inductive Reactance

Reactance of a coil, called inductive reactance, is devoted by XL and is given by $XL = 2\pi$ (pi) f.L.......(1). where $\pi = 3.142$, f is the frequency of the applied EMF in HZ and L is inductance of the coil in Henries. If the frequency is given in kilo-hertz and the inductance in milli-henries, then also the same formula holds good.

4.2. Capacitive Reactance

Reactance of a capacitor, called capacitive reactance is denoted by XC and is given by

$$XC = \frac{1}{2\pi fc} \qquad \text{.........(2)}$$

where $\pi = 3.142$, f is the frequency of applied EMF and C is the value of the capacitor in farads.

Both inductive and capacitive reactances are measured in ohms.

4.2. Phases of Current and Voltage in a Coil and capacity.

It can be proved mathematically as well as graphically that current through an inductor (coil) lags behind the applied voltage by 90° and current at a capacitor leads over the applied voltage by 90°

4.3. Resonance

It is apparent that if both the circuit elements, a coil and a capacitor are connected in a single circuit their reactances will oppose each other and the resultant reactance will be the difference between the two. Two circuit configurations of coils and capacitors are usually encountered in electronic circuits : (1) the Series Tuned circuit wherein the coil and capacitor are connected in series with the applied emf (2) the Parallel Tuned circuit wherein these two components are connected in parallel to the applied emf.

Since the resultant reactance of either circuit is the difference between the inductive and capacitive reactances a case arises when both of them are equal. In that case, the difference between the two reactances is zero. Such an eventuality is known as resonance, and takes place at a particular frequency of the applied EMF at which both the capacitive and inductive reactances cancel out each other. This particular frequency is known as the resonant frequency of the circuit.

Mathematically, we are considering the situation when

$$XL = XC$$

i.e. $$2\pi f L = \frac{1}{2\pi f C}$$ Where f is the frequency of the applied emf in HZ.

or $$f^2 = \frac{1}{4\pi^2 LC}$$

or $$f = \frac{1}{2\pi\sqrt{LC}} \qquad \text{.......(3)}$$

EQ (3) gives the resonant frequency of the circuit. If the frequency of the applied EMF is given in KHZ and the values of the

inductance and capacitance are given in micro henries and picofarads respectively, eq (3) can be re-written as

$$fr = \frac{10^6}{2\pi\sqrt{LC}} \quad (4)$$

Where fr is the resonant frequency in KHZ, L is in μH and C is in picoF.

EQ (4) is of practical utility. Certain occasions arise when we are given the resonant frequency and have to find the value of the inductance or capacitance of the resonant circuit. This is achieved with the help of the following equations :

$$L = \frac{25300}{fr^2\ C} \quad \ldots\ldots(5)$$

Where L is in μH

C is in μF

and fr is the resonant frequency in KHZ

$$C = \frac{25300}{fr^2\ L} \quad \ldots\ldots(6)$$

where the letters denote the same quantities as in eq (5)

Remember that at the resonant frequency of both the Series tuned circuit and the Parallel tuned circuit the reactance is zero and equations (3) through (6) hold good.

5. **Impedance** : Every coil of wire has some resistance due to which some magnetic energy stored in the coil is lost in the form of heat. The effect is that a coil always has to be considered as if a resistor were connected in series with it. This is true both in case of series and parallel tuned circuits.

The combination of reactance and resistance is known as impedance. Impedance is not just the arithmetic sum of reactance and resistance; it is calculated by the vectorial summation of the two quantities : reactance and resistance.

Impedance is denoted by the letter Z and is measured in ohms.

6. **Tuning** : We have written about resonant frequency. It is now necessary to have clear concepts about the significance of resonant frequency. In both the series and parallel tuned circuits at the particular frequency of the applied EMF when the inductive and capacitive reactances become equal and cancel each orther, certain specific properties are exhibited by the two circuits.

Series Resonant Circuit :

At the resonant frequency, the impedance of the circuit is minimum (equal to the value of the series resistor only). As such, the circuit passes the maximum amount of current from the source of applied EMF through the circuit at this frequency. At all frequencies other than the resonant frequency, impedance of the circuit increases and the amount of current passing through the circuit decreases.

Parallel Resonant Circuit :

At the resonant frequency, the impedance of the circuit is maximum and is given by the equation,

$$Z = \frac{L}{CR} \quad \ldots(7)$$

where Z is impedance in ohms, R is resistance in ohms L is inductance in henries and C is capacitance in farads.

As such, minimum amount of current is taken from the source at the resonant frequency.

At all other frequencies, the impedance offered by the circuit to the source keeps decreasing as the difference between the resonant and non-resonant frequency increases. It will be seen that the properties of a parallel resonant circuit are opposite to those of the series resonant circuit.

Thus, we come to the remarkable conclusion that a coil and a condenser connected in series or parallel configuration possesses the property of discriminating in favour of one particular frequency against all others. When the values of the circuit components (L and C) are such that the circuit frequency given by eq 3 $\left(\frac{1}{2\pi\sqrt{LC}}\right)$

is equal to the frequency of the applied emf, the circuit is said to be tuned to that frequency; that is, the circuit then, selects that particular frequency and discriminates against all other frequencies.

The process of tuning is the basis of all radio circuits: otherwise, it will not be possible to receive the desired radio transmitting station out of the innumerable stations propagating electromagnetic waves.

7. Coil Selectivity (Q). It is also known as the efficiency factor of the coil. It is the ability of the coil to resonate accurately to a particular frequency to the exclusion of other frequencies. It is denoted by the letter Q and is given by the equation:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \quad \ldots (8)$$

EQ (8) can be simplified thus:

At resonance, we have seen (eq 3) that

$$2\pi f L = \frac{1}{2\pi f C}$$

$$\text{or } (2\pi f)^2 L = \frac{1}{C} \quad \ldots (8a)$$

Taking square root of both sides of eq 8 (a), we get

$$2\pi f\sqrt{L} = \frac{1}{\sqrt{C}} \quad \ldots 8\,(b)$$

Substituting the value of $\frac{1}{\sqrt{C}}$ from equation 8 (b) in equation (8), we get

$$Q = \frac{1}{R}.2\pi f\ \sqrt{L}.\ \sqrt{L}$$

$$= \frac{1}{R}.\ 2\pi f L$$

$$= \frac{wL}{R} \ldots (9)$$ where w stands for $2\pi f$.

From eq (9), we get the definition of Q as the ratio of the inductive reactance of a coil to its resistance.

However, eq (8) gives a better concept of the Q of a coil. It shows that the selectivity of a coil is inversely proportional to the resistance of the coil and directly proportional to the ratio L/C i.e. larger the inductance and smaller the capacity of the tuning circuit, greater is the Q of the coil.

2

Design of Coils/Transformers

1. As will be evident from Chapter I, coils and transformers are used in alternating current (AC) circuits. The requirement is to design a particular coil or transformer, so that it should possess the requisite value of INDUCTANCE.

Inductance, as we have seen, depends on

(*a*) the rate of change of current,

(*b*) the geometrical configuration of the coil or transformer.

We shall now investigate how frequency of operation is related to the inductance of a coil.

2. **Coils.** Design of an item, obviously, depends on the work it is expected to perform.

In electronic circuits, coils are employed for the following functions:

(1) to work as resonant circuits in conjunction with a suitable value of a fixed or variable capacitor e.g. antenna coils and oscillator coils. IFT's (Intermediate frequency transformers) used in superhet receivers are, in fact, coils possessing the requisite inductance to resonate at the intermediate frequency in conjuction with a fixed capacitor.

(2) to work as chokes e.g. smoothing chokes are employed in the dc power supply circuits to eliminate voltages at ripple frequencies; chokes are employed in audio frequency circuits as loads in tube or transistor stages.

3. **Design of Coils in Resonant or Tuning Circuits.** To determine the inductance of the coil for tuning circuits it is first necessary to consider the wave—range which the coil is to cover in conjunction with a variable capacitor. The variable capacitor has maximum and minimum values, the stated capacity being the maximum. Wavelength of alternating currents is denoted by the symbol λ which is related to the frequency of the AC by the equation

$$\lambda = \frac{3 \times 10^8}{f} \qquad \ldots(10)$$

where λ is the wavelength in meters

f is the frequency in HZ

and 3×10^8 is the velocity of electromagnetic waves.

The wave-range will have two extreme wavelengths : the maximum wavelength when the variable capacitor is fully meshed in (maximum capacity) and minimum wavelength when the variable capacitor is fully opened. When the value of the tuning capacitor is known the value of the inductance required to tune over a particular wave—band is calculated from the following equation:

$$(\lambda\ max)^2 - (\lambda\ min)^2 = (1885)^2\ LC \qquad \ldots(11)$$

Where λ is in meters, L is in microhenries and C is in microfarads.

Example 1. It is required to tune from 400 KHZ to 1 MHZ using a ·0005 MFD Capacitor.

Solution. 400 KHZ = 750 meters

1 MHZ = 300 meters

Using eq (11), we have

$$(750)^2 - (300)^2 = (1885)^2\ L\ \frac{5}{10^4}$$

$$L = \frac{[(750)^2 - (300)^2] \times 10^4}{(1885)^2\ 5.}$$

$$= \frac{472500 \times 10^4}{17766125}$$

= 266 microhenries approx.

3.1 In cases where a fixed capacitor is used the resonant frequency of an LC tuned circuit is found from the equation

$$\lambda^2 = (1885)^2 LC \qquad \ldots (11a)$$

where all the symbols have the same meanings as in equation 11

4. Having determined the value of the required inductance, the geometrical configuration of the coil is to be worked out.

The geometrical configuration of a coil depends upon (1) the type of former used, (2) the type of core used, (3) the size of wire used (4) the number of turns wound on the former and (5) the type of winding used.

A brief description of the above factors constituting the geometrical configuration of a coil will be given. This description will be followed by a number of equations which relate the inductance with the geometrical configurations of a coil.

4.1. Types of formers. Formers are the devices on which the coils are actually wound. They are made of insulating materials such as ceramic, paxolin, ebonite, plastic or cardboard. Ceramic formers are usually used in applications above 30 MHZ since ceramic is characterised by low dielectric constant resulting in low loss at high frequencies, and also because ceramic is not much affected by temperature and humidity. At short, medium and long wavelengths, paxolin or ebonite tubes are used as formers. At mains power frequencies, cardboard or plastic formers are used.

4.2. CORE TYPES:

Air Core. Core is the space available inside a former. When no material is inserted within the former, the coil is said to have air core. In air (or in any non-ferromagnetic material) all the magnetic lines produced by the changing current do not link with every turn of the coil: many of them are lost in the surrounding space. Thus, the value of the inductance in air-cored coils is very much reduced.

4.3. Iron-Core. Iron is a ferromagnetic material. When the space inside the former of a coil is filled with iron the lines of flux produced by the AC flowing in a coil find a much easier path through

the iron, and do not tend to "leak" to the outside of the coil; instead, the lines of flux produced by the alternating current complete their paths through the iron. In addition, when a current flows in a coil, the iron becomes magnetised and adds its own flux lines to those produced directly by the current. Thus, the total flux linkage i.e. the inductance of the coil is much greater in an iron-cored coil than in an air-cored coil of the same dimensions.

4.4. However, the use of a ferromagnetic material (such as iron) as the core of a coil has its limitation.

The magnetic flux produced by the alternating current flowing through the coil cuts the iron core also; as such an emf is induced in the iron core (Faraday's Law). This EMF causes large circulating currents in the core and are termed "Eddy Currents". They represent an expenditure of energy which only heats up the core unduly and is likely to damage the insulation of the winding. The effect of the eddy currents is quite pronounced even at the low mains supply frequency (50 HZ)

Eddy currents are kept down to a very low value by "laminating" the cores, that is, by making them up in a number of thin sheets of iron laid together and insulated from each other by varnish, shellac or tissue paper. In this manner, the Eddy currents are forced to travel in very narrow high-resistance paths and are kept down to such a small value that their effect is not serious. The laminations are usually 'L' shaped, being pushed inside the coils from alternate ends.

However, even with well-laminated iron cores, the losses at radio frequencies due to eddy currents render their use prohibitive. This is because the eddy current losses increase with frequency and so the inductance of the coil decreases, as the frequency increases. This may be so pronounced that the inductive reactance of an iron-cored coil remains nearly constant over a large range of radio frequencies or even falls as the frequency increases. In general, use of laminated iron-core in coils is limited upto the highest audio frequency (about 20 KHZ)

4.5. Powdered Iron Cores. Upto about 1933, the tuning of circuits was carried out principally by means of variable capacitors and fixed

inductances. Owing to large eddy current losses, it had not been possible to use laminated iron-cored inductances in RF circuits. In 1933, special low-loss powdered iron cores were developed. The powdered iron dust particles are coated with insulating cement. By subjecting the coated dust particles to high pressures in moulds, they are bound together, and a material of low eddy current loss and yet of high permeability is obtained. The mould is so designed as to be capable of variation inside the coil. As the mould containing the iron dust particles is varied, the magnetic flux and, therefore, the inductance of the coil is varied. Thus, by varying the coil inductance the frequency of the tuning circuit is varied. This method of tuning is known as permeability tuning. A coil with powdered iron core has a high Q. The operating frequency range is usually between 5HZ to 500KHZ.

4.6 Ferrite Core is used in coils in the frequency range covering audio feequencies and radio frequencies upto 100 MHZ. Ferrites are made of electrically non-conductive crystals of the mixture of manganese ferrite and nickel ferrite, and fabricated through a binding process and heat treatment of the crystals. Ferrites possess high magnetic permeability and high resistivity to eddy currents. Ferrite core is also known as pot core.

Note : Because of its high resistivity, the electrical continuity of a ferrite material connot be checked by a multimeter.

4.7. Size of Wire and Number of turns. Size of wire refers to the diameter of the wire in inch or millimeter used for winding a coil. Wire sizes have been standardized in two systems : in the British system they are known as standard wire guage (SWG) and in the American system, wires are available in American Wire Guages (AWG). These guages are mere numbers wherein the larger number denotes a thinner wire than a smaller number.

These wires are copper wires covered with a coating of an insulating material, such as enamel, silk or cotton. The size of the wire and its insulation coating determine (a) the number of turns that can be given to the wire per inch of its length, safely without the risk of cracking its insulation. (b) the amount of current that can be safely

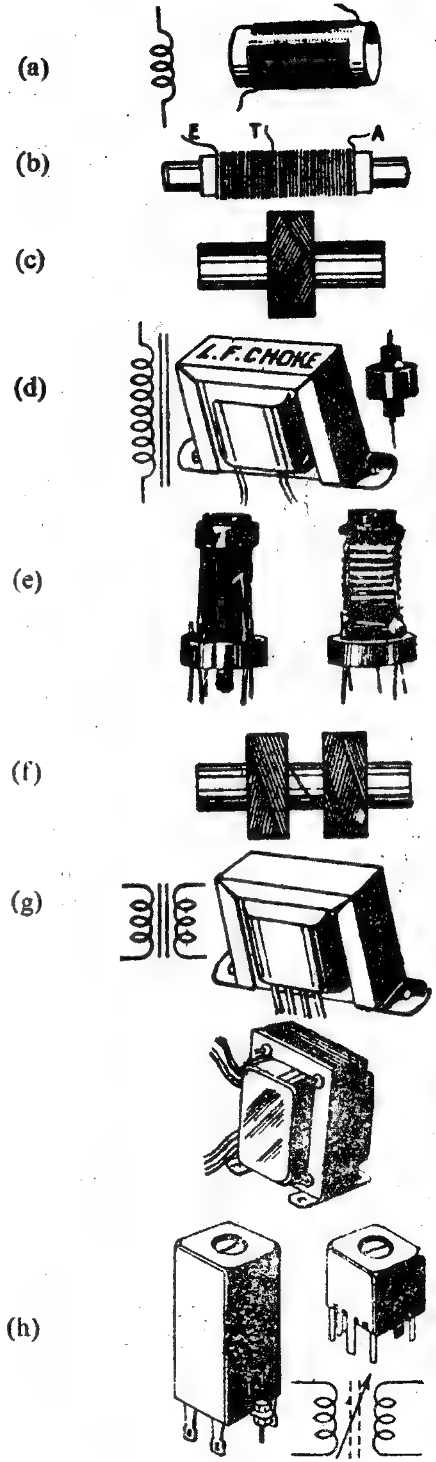


Fig. 1. Various Types of Coils and Transformers

carried by the wire without the risk of its being fused, (c) its resistance in ohms per unit of weight (usually lb),

(d) the frequencies on which it is to be used. Thinner wires are used on short waves.

The relevant details of the wire sizes (in SWG) are given in Table IV.

4.8. Types of Winding

Single-Layer Simple Winding

As the name indicates the wires are wound on the appropriate former in one layer. It is wound from the bottom to its top, and then the starting and ending terminals are anchored at tags fixed at two ends of the former. A single layer RF choke is shown in Fig. 1. (a)

4.9 Toroidal Winding. A toroidal wound coil is also a single layer would coil, but it is wound on an iron or ferrite anchor ring.

It provides high permeability, and hence high inductance value which is independent of temperature and AC-DC levels. The operating frequency ranges from 5HZ to 50 KHZ. It can be stacked close together without being affected by unwanted mutual inductive coupling from other coils. Also, the symmetrical winding of this coil produces an extremely low hum pick-up.

The usual applications of a toroidal coil are wave filters, oscillators, discriminators and power supply filters.

4.10 Multilayer Coils. In winding a multi-layer coil, the straight forward method is to wind the wire along the former in one layer and then to wind another layer above the first one in the reverse direction until the starting point of the winding is again arrived at, and so on. Multilayer coils wound on an iron former is shown in Fig 1 (c) and (d).

4.11 Self Capacity of a Coil. Now, the multilayer wound coil described in the foregoing paragraph has one predominant short coming—its self capacity increases considerably. This is explained below.

The result of a simple multilayer winding is that the adjacent turns in the windings are found to be at very different potentials. In a two layer winding, for example, the first and the last turns wound would be adjacent, and their difference of potential would be the total P.D across the winding. They are separated from each other by the insulation of the wire, and form, in effect, a condenser.

It is obvious that the condenser so formed is in parallel with the total winding. In a similar manner every turn of the winding has a certain capacity in parallel with the inductance of the coil. The coil thus, really becomes a parallel resonant circuit, and instead of its reactance increasing steadily with frequency (XL=WL), it rises to a peak value at the frequency at which the relf-capacity of the coil tunes with its inductance. As we have already noted, at its resonant frequency, a parallel resonant circuit behaves as a very large resistance, and it will be obvious that even at frequencies removed from resonance, this tendency will always be in evidence, that is, the effect of the self-capacity of the coil is to increase the AC resistance of the coil. In a single layer coil, the effect of self-capacity is not so large, because the adjacent turns do not differ so much in potential.

The effect of self-capacity in a multi-layer coil can be decreased by the following methods:

(*a*) by winding the turns on top of each other in the same plane or

(*b*) by arranging the layers in a bank-winding or

(*c*) by adjusting the thickness of the air spacing between turns and layers (space winding).

4.12 Bank Winding. The method of bank-winding several layers of a coil is shown in Fig 2.

The order in which the turns are wound on the former is shown by the numbers in the figure. Note that this type of winding a coil is widely used to construct IF (Intermediate Frequency) transformers of a superhet radio receiver.

4.13 Space Winding. Another method of minimising the self-capacity effect of a coil is to adjust the thickness of the air spacing

between turns and layer. This is achieved by the "one-diameter thickness" rule which is described below. Take two lengths of the same wire guage to be used. Wind them side by side on the former. Strip away the spacing wire after varnishing. Thus, the spacing of the same dimension as the dameter of the wire is achieved. Coils can be wound with larger or smaller then one diameter of the coil wire by using appropriate guage of the wire between the turns.

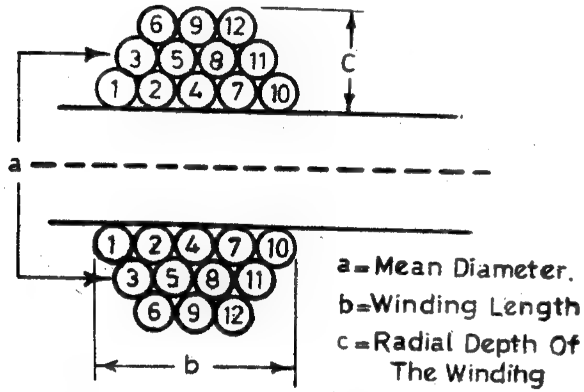


Fig 2

Note that larger spacing reduces the self-capacity of the coil, but at the same time reduces the inductance of the coil significantly. It has been found that spacing of one diameter thickness of the same guage of wire which is used for making the coil is quite adequate to reduce its self capacity for all practical purposes, yet retaining the requisite inductance value of the coil.

Note that above about 100 m wavelengh (i.e. below 3MHZ), spacing between the turns may be dispensed with whereas above about 30 MHZ spacing is essential.

5. Relationship between inductance and the physical configuration of the coil.

In para 3 we have seen how inductance of a coil is related to the frequency of the current flowing through it. We are now in a position to enunciate the relationship between the coil inductance and its physical properties as described in the foregoing paragraphs.

The inductance for a particular coil is determined by the following constructional factors:-

1 Number of turns of wire wound upon the coil : Inductance is directly proportional to the square of the number of turns. Thus, larger number of turns imply more inductane and therefore lower frequency of operation.

2 The length of the coil : Inductance in inversely proportional to the length of the coil. Thus longer coil winding implies less inductance and therefore higher frequency of operation.

3 Permeability of the core material : Inductance is directly proportional to the permeability of the core material.

4 Cross sectional area of the core : Inductance is directly proportional to the cross-sectional area of the core under the coil.

Keeping the above factors in view, a number of equations have been established by electronic scientists to relate the inductance of a coil with its physical properties. When suitable data are available, then the unknown quantity can be calculated by substituting the known data in the appropriate equation.

5.1. Equations applicable to various coils : We shall now list some of the equations which are employed in coil construction.

(a) Applicable to Single-Layer Air Core Coils.

$$L = \frac{r^2 \times N^2}{9\,r + 10\,l} \qquad \text{. . . EQ12}$$

where L is the inductance in micro -H,

r is the outside radius the coil in inches

l is the length of the coil in inches

and N is the number of turns of wire required

(b) Applicable to Air-Cored Multilayer Coils

$$L = r \times N^2 \times F \qquad \text{. . . EQ 13}$$

where L = inductance in micro —H

r = mean radius of the coil in inches, i.e. radius of the former plus half the depth of the winding.

F = form factor of the coil

F, the form factor of the coil, is found by the following formula

$$F = \frac{r}{l + d}$$

where l = winding length in inches

d = depth of the winding in inches.

The corresponding value of F is found from the graph of

F against $\frac{r}{l + D}$ shown in Table V

(c) Applicable to Toroidal coils wound on Ferrite Ring Cores:

$$L = (\text{'}0046\ u\ N^2\ h\ \log_{10} \frac{OD}{ID}) \qquad \ldots 14$$

Wheye L = inductance in micro —H

N= Number of turns
OD = Outside diameter of Core in inches
ID = inside diameter of Core in inches
h = height of core in inches
u = permeability of the core material.

(d) Applicable to Bank Wound Coils.

$$L = \frac{.2\ a^2\ N^2}{3a + 9b + 10\ c} \qquad \ldots \text{EQ } 15$$

Where L = inductance in micro —H

a = mean diameter of the coil in inches
b = winding length in inches
c = radial depth of the winding in inches

For the dimensions a, b and c, see Fig 2.

(e) Applicable to iron/ferrite cored coils:

$$L = \frac{4.06\ N^2\ \mu A}{27 \times l} \qquad \ldots \text{EQ } 16$$

where D is inductance in micro-henries
N is the number of turns
A is the cross-sectional area of the coil in inches
l is the length of the coil in inches
μ is the permeability of the core-

(Typically $\mu = 1000$ for Silicon iron

and $\mu = 2000$ for ferrites)

Note: However, it is emphassed that eq 16 is only a guide to obtain the inductance of an iron or ferrite cored coil. As a matter of fact, no equation exists to assess the inductance of such a coil accurately. What is actually done is to estimate roughly the required inductance from eqs. 11(a) and 12 through 15 applicabie for air-cored coils, and then trim the required inductance with core of ferro-magnetic materials by trial in actual circuit.

The variation of inductance obtainable with adjustable slugs depends on the winding length and the size and composition of the core and no universal correction factor is available.

However, as a general rule, for coils having a winding length of .3 to .8 inches a dust iron core will *increase* the inductance to about twice the air-core value; a brass core will *reduce* the inductance by about .8 times the air-core value.

5.2. Computation of Coil Design : In order to facilitate quick computation of the resonant frequency using LC circuits, Table VI shows the calculation of the inductance required for a particular value of a capacitance. Table VI also shows the winding data using a 7/16 in diameter former. An example will illustrate how to use this Table.

Example 2 : It is required to wind a coil on a former 1/16 in diameter which will resonate at 7MHZ with a 50 pF Capacitor.

Solution :

(1) Draw a straight line through 50 pf (Axis A) and 7 MHZ (Axis B).

(2) Project the line to cut axis C and read off the required inductance which is about 10.3 uH.

(3) Draw a horizontal line through 10.3 uH on axis D and a vertical line through a reasonable winding length (say, .5 inch) and determine the most suitable wire guage to use i.e 32 SWG,

(4) From the 32 SWG curve determine the winding length to give an inductance of 10.3 uH i.e. .48 in.

Conclusion : The coil will, therefore, be close wound with 32 SWG enamelled copper wire and .48 inch long. From the SWG Table IV, we find that the turns per inch for 32 SWG enamelled copper wire is 86. Hence a winding .48 inch long will consist of (86 x .48) =41. turns approx.

5.3 Space Winding :

At high frequencies, the inductances will be low. For coils of inductance less than 1 micro—H. it is necessary to space wind (rather than close wind) with a heavy guage wire. In Table VI, therefore, curves have been provided for pitches of 10,15 and 20 turns per inch.

Example 3 : It is required to wind a coil of inductance .5 μH.

Solution :

Since the inductance is less than 1 μH, the coil is to be space wound.

In Table VI, ..5μH cuts the 20 TPI line at a point corresponding to .4 inch winding length.

Let the wire guage be 26SWG. As per Table IV 26 SWG has 50 turns per inch. A length of .4 inch will, therefore, have

$$50 \times \frac{4}{10} = 20 \text{ turns}$$

But as per Table VI, only 20 turns per inch should be wound, i.e. a length of .4 inch will have

$$20 \times \frac{4}{10} = 8 \text{ turns}$$

In other words, on a former of 7/16 inch diameter, a coil made of 26 SWG wire should occupy .4 inch length of the former using only 8 turns whereas the 26 SWG wire can give 20 turns on the same length; that is, number of turns will now be slightly less than half the number of rated turns of SWG 26 wire This implies that the distance between adjacent turns will be the diameter of the coil wire. This is space-winding.

4.4 Table VII shows the winding data of a coil using a former of diameter 3/10 inch instead of 7/16 inch. Tables V and VII should enable a hobbyist to estimate the inductnnce, cable guage and number of turns required to wind most of the types of coils used in radios such as antenna and oscillator coils.

Oscillator Coils : The common difficulty about designing oscillator coils is that tuned circuit formed by the coil has to resonate continuously over a frquency range higher than the incoming frequency range. An example will clarify this point.

Assume that the main tuning circuit is to cover 200 to 500 meter (i.e. 1500 KHZ to 600 KHZ). The oscillator coil, then, for an intermediate frequency of 460 KHZ will be working between the range 1960 to 1060 KHZ. Thus, the ratios of maximum to minimum frequencies are different: it is 1 to 2.5 for the tuning coil and 1 to 1.84 for the oscillator coil. Hence, the steady differcnce of 460 KHZ will not be maintained by straight ganging. To correct this, a system of padding and tracking condensers is arranged into the oscillator circuit.

6. Design of I.F. Transformers.

IFT's are generally bank wound. The coils are coupled by mutual inductance. Modern IFT's used in Radio receivers are invariably wound on formers containing ferrite cores. These cores are adjustable i.e. they may be screwed In or out of the former. The coils of the IFT are wound as shown in Fig. 2.

By adjnsting the core the magnetic coupling between the primary and secondary of the transformer is varied. This method is known as permeability tuning.

No specific formula exists to calculate the coil windings of transformers using permeability tuning. What is done is this :

The inductance, and the number of turns required are calculated using equations 11 (a) and 15. Next, the number of turns are trimmed keeping in view (a) output impedance of transistor or valve stage in respect of the primary winding and the input impedance of the transistor or valve stage in respect of the secondary winding, and (b) the changes in inductance introduced by the magnetic path created by the ferrite core. The complete procedure for designing a transistor IF stage in a step-by-step manner is given below :—

Complete Design Procedure of Transistor IF Stage :—

We shall take the circuit of the Ist IFT of a typical transistor radio.

The design is carried out in accordance with the following steps:-

1. Find the output impedance of the stage.
2. Find the inductance of Primary required for resonating at 455 KHZ
3. Find No of turns required
4. Find SWG of Coil
5. Find resistance (R) of primary
6. Find Q of the primary. Relationship between the resonant frequency fr, Q and bandwidth is given by $QP.QS = 2.25/K^2$ where QP and QS are primary and secondary Q'S and K= Bandwidth/Resonant frequency.
7. Find Dynamic impedance L/CR and check whether it is compatible with Step I above. If the dynamic impedances are very much incompatible, change the value of the tuning capacitor, C. Of course, this will need readjusting steps 2 to 6.

8. In this connection the following points are to be borne in mind.

(a) increasing the ratio L/C increases the Q of the circuit (EQ8) and

(b) the action of AVC which is normally applied to an IF stage imposes a limit of the decrease of C. The above two requirements are conflicting and a compromise is effected. Normally the Q of an IFT should be between 50 and 120, and the value of C lies somewhere betwcen 100 picoforad to 300 picofarad.

Example:- (To illustrate relationship between resonant frequency, Q and band width of a Coil) An IFT is tuned to a resonant frequency of 455 KHZ. What values of circuit Q's are necessary to provide response for a 10KHZ band-width.

Given = Band width 10KHZ

fr = 455 KHZ

Find QP, QS

Solution $K = \frac{\text{Band Width}}{fr} = \frac{10}{455} = .0219$

$$QP.QS = \frac{2.25}{K^2} = \frac{2.25}{(.0219)^2} = 4691$$

If QP = QS then

$$QP = QS = \sqrt{4691} = 68$$

The design of an IFT will be illustrated by the circuit diagram of the Ist IF stage using BC 194. Assume that the above stage is operated with a collector current of lmA. The Q of the IFT is 60, only the primary is tuned. Bandwidth of the IFT is 4.5 KHZ. IF is 455 KHZ

The applied EMF is 6V which is fed to the collector of BC 194 via a resistor of 440 ohms.

Collector Current of BC 194 $= \frac{6}{Z} = 1ma = \frac{1}{10^3}$ amp

The output impedance

$$Z = 6 \times 10^3$$

Now Z = A resistor of 440 ohms in series with the dynamic impedance of the tuned circuit given by L/CR

$$440 + \frac{L}{CR} = 6000$$

$$\text{or } \frac{L}{CR} = 6000-440 \qquad \omega = 2\pi f \qquad \ldots (1)$$

$$= 5560$$

$$\text{Next, } Q = \frac{WL}{R} = 60 \qquad 6.28 = 2\pi$$

$$\text{or} \qquad \frac{6.28 \times 455 \times 10^3 \times L}{R} = 60$$

Multiply both Sides by $\frac{1}{C}$

$$\frac{6.28 \times 455 \times 10^3 \times L}{CR} = \frac{60}{C} \qquad \ldots\ldots (2)$$

Substituting the the value of $\frac{L}{CR}$ from (1) into (2) we have

$$6.28 \times 455 \times 10^3 \times 5560 = \frac{60}{C}$$

Converting the value of C into Pico farads, we have

$$C = \frac{60 \times 10^{12}}{6.28 \times 455 \times 10^3 \times 5560}$$

$$\simeq 3775 \text{ pf}$$

Allowing about 30 per cent for losses due to stray capacities, we arrive at a tuning capacity of 2700 pf. The value of the inductance to tune it to 455 KHZ is found from the formula :

$L = \frac{25300}{fr^2C}$ where fr is the resonant frequency in KHZ, L is the inductance in uH and the capacity is in uf

$$= \frac{25300}{(455)^2 \times \frac{2700}{10^6}}$$

$$= \frac{25300 \times 10^4}{(455)^2 \times 27} \qquad \ldots\ldots (3)$$

Solving eq 3 we get

$$L \simeq 47 \text{ uH}$$

IF Transformers used for transistor applications have much smaller dismensions than those employed in valve circuits. This is because of the extremely low currents and voltages involved.

Usually, as already stated, the IFT's are bank wound. As such the number of turns required can be found from the formula :

$$L = \frac{.2\, a^2 N^2}{3a + 9b + 10C} \qquad \ldots\ldots (4)$$

Where in the case of IFT's of transistorized sets.

$$a = \frac{1}{2}''$$

$$b = \frac{1}{8}''$$

$$c = \frac{1}{8}''$$

the diamensions a, b and c being those shown in Fig. 2.

Substituting these values in eq. (4) and solving for N we get

$$N = 42 \text{ turns approx}$$

Now since b and c are $\frac{1}{8}''$ or .13" approx. we conclude that we should use a wire guage which will give 323 turns per inch approx. This is found as follows : since .13" gives 42 turns, 1" will give

$$\frac{42}{.13} = \frac{42 \times 100}{13} = \frac{4200}{13} = 323 \text{ turns approx}$$

A scrutiny of the SWG table IV will show enamel copper wire of 45 SWG gives 322 turns per inch. Thus the primary winding of IFT 1 will have 42 turns of 45 SWG wire to give a Q of 60.

Coil Construction

After the inductance, method of winding (single layer, multilayer or bank winding) and the associated capacitor have been calculated, the type of former is chosen. The formers can be paxolin or wooden dowels. While making bank-wound coils, it is suggested that some of the commercially available coils should be inspected. These are machine wound. For hand winding, care should be taken to ensure that each layer is kept even, tightly packed without lumping or cross over and that the insulation of the wire does not get cracked. If a coil is to be tapped, NEVER cut the wire and solder the tapping leads. Instead, draw out six inches or so of the wire, fold the length into a long loop and carry the wire back to continue the wiring. The looped wire can then be bared and connected outside the coil: this way, there will be no risk of a breakdown in the insulation. These wires should be taken to soldering tags and the simplest method is to drill two small holes at the desired point ¼" apart and to run the double loop of wire through them. The winding is then soldered to the loop inside the former and carried to the starting point of the winding by the most direct route, through a third drilled hole.

When baring the ends of the wire for soldering, silk, and cotton covering should be cleared by dipping its end into methylated spirit and wiping it with a rag. When the coils are wound, they should be protected against humidity. This is achieved by spreading varnish or wax over them : this procedure gives them strength and rigidity. The best varnish for this purpose is polysterene which may be made by dissolving polysterene formers in benzole. Normally the coil is immersed in the varnish and then it is drained very thoroughly.

When the varnish is dry "space turns" if used (see para 4.13) can be removed.

If the coil is to be given a protecting layer of wax, then melt the wax and boil it, so that any water contained in it is drained off. Then the coil is dipped in the molten wax and allowed to remain until all the air bubles are driven off.

Wooden formers if used for IF transformers should be boiled in the wax before use. When the wax has hardened after cooling the coil will be very firm and all surplus wax must be removed.

Screening of IFT'S

Enclosing a coil in a screening can lower the efficiency (Q) of the coil. Without going into cumbersome calculations regarding drop in inductance due to the screen, a rough rule for keeping the 'Q' of the coil high is to make the diameter of the can at least twice (if not more) than that of the coil. Greater spacing is desirable if the IFT DOES not become bulky.

Output Transformers

The purpose of this type of transformer is to match the impedance of a loudspeaker or a number of loudspeakers to the optimum load of the tube or transistor. In other words, the transformer transforms the impedance of the speaker, so that the impedance which it presents to the primary winding is equal to the load of the output stage active element (tube or transistor)

The principle involved is that the impedance ratio of a transformer is equal to the square of the turns ratio.

Table IX enables quick computation of the Turns ratios for given load and speaker and impedances. Typical IFT's are shown in Fig 1 (h).

We shall illustrate the functioning of an output transformer by an example.

Given (i) β of transistor = 100

(2) AV (Voltage gain) = 128

(3) Resistors R_1 and R_2 of values 20k and 40k respectively forming a potential divider across Vcc+supply voltage of 12V, to provide base bias to the transistor stage,

(4) R_3 is the emiter bias resistor of 4K,

(5) Impedance of the loudspeaker connected to the secondary of the output transformer is 8 ohms.

Find the transformer design details

Solution :

Step 1 $= I_E = \frac{E_B}{R_3} = \frac{Vcc \times R1}{(R1 + R2)\, R3}$

$$= \frac{12 \times 20000}{(20{,}000 + 40{,}000) \times 4000} = 1 \text{ mA where IE is emitter}$$

current

Step 2 $=$ re (input resistance) $= \frac{25}{IE}$ (Shockley's theorem)

$$= \frac{25}{1} = 25 \text{ ohms}$$

Step 3 ro (Output resistanee)

$= 8.\left(\frac{Np}{NS}\right)^2$ The figure 8 denotes the loudspeaker impedance. NP and NS are the number of turns in the Primary and Secondary respectively

Step 4 AV (Voltage gain)

$$= \frac{ro}{re} = \frac{8.\left(\frac{NP}{NS}\right)^2}{25} = 128 \text{ (Given)}$$

Step 5 $\left(\frac{NP}{NS}\right)^2 = \frac{128 \times 25}{8} = 400$

or $\frac{NP}{NS} = \sqrt{400}$

$$= 20$$

This means that the ratio between the Primary number of turns to the secondary number of turns is 20 : 1

Step 6 $\frac{\text{Primary impedance. Zp}}{\text{Secondary impedence Zs}} = \left(\frac{NP}{NS}\right)^2 = 20^2 = 400$

Now $Zs = 8$

$\therefore Zp = 400 \times 8 = 3200$ ohms

Step 7. Now the problem is to ascertain the relationship between impedance of a winding and the number of turns required to achieve this impedance. As already stated, no specific formulas exist to correlate these two parameters in the case of iron-cored transformers/chokes which are commonly used in audio frequency circuits. However, certain relationships have been worked out, based on practical AF transformer construction. These relationships are tabulated in Table VIII.

From Table VIII, for each value of dimension (length and thickness of winding) referenced to a 1000 ohm impedance we obtain a figure which gives the optimum number of turns required to provide 1000 ohm load impedance. To derive the uumber of turns required to achieve the desired load impedance we have to use the following equation :

$\sqrt{\frac{\text{Desired Impedance}}{1000}} \times$ Figure obtained from Table VIII

Now, say, we want an output transformer of mid-band losses of 5.4% which is tolerable. Correspondingly, we obtain the following data :

Length of the winding : $1\frac{1}{4}$

Thickness of the winding : $1\frac{3}{4}$

Number of Turns for 1000 ohms : 700. Hence for the desired 3200 ohms primary impedance (Step 6), the number of turns required will be

$$\sqrt{\frac{3200}{1009}} \times 700 = 1260$$

Secondary Turns : $\frac{NP}{NS} = 20$ [Step 5]

$$\therefore NS = \frac{NP}{20}$$

$$\text{or } NS = \frac{1260}{20} = 63$$

Step 8 : SWG and Constructional details

Refer to Table IV

Here layer winding will be used for the 1260 turns Using 36 SWG enamelled wire of 120 turns per inch gives 150 turns per layer $(1\frac{1}{4})''$. This requires $\frac{1260}{150} = 8.5$ layers approx. 8.5 layers will take $8.5 \times .007 = .0595''$ for the wire. [The figure .007 represents the diameter of SWG wire from Table IV]. At .003" per layer insulation, it will take .0255". Thus, the depth of the primary winding will be $.0595 + .0255 = .085''$. Secondary : 63 turns will be wound with, say, 20 SWG enamelled wire of 26 turns per inch. This gives 32 turns per layer ($1\frac{1}{4}''$). Number of layers will be 2. Two layers will take $.036 \times 2$ .072" [The figure .036 represents the diameter of 20 SWG wire]. At .003" per layer insulation it will take .006". Ths, thie depth of the secondary winding will be $.072 + .006 = .078''$. Hence total (primary plus secondary) winding depth will be $.085 + .078 = .163''$. This will leave sufficient room for insulation between windings and on top.

POWER TRANSFORMERS

Transformers used in power supply circuits are known as power transformers. They consist of two coils or sets of coils as in the case of all transformers. They differ from other transformers in at least two respects: firstly, they are invariably wound on an iron core to assist the coupling between them and thus improve their mutual inductance; and secondly, they are operated at comparatively high power ratings.

We shall now consider the power transformers used in AC Mains circuits. In our country the AC Mains supply is 220 V 50 HZ per phase. The frequency of the supply is also important. Remember that a transformer designed to operate on a particular frequency must not be used on a *lower* frequency. But the same transformer could be used on a higher frequency. For example, a power transformer designed to be operated on 5O HZ should not be operated on a frequency of 25 HZ but it can safely be used on a 100 HZ Supply.

Power from AC is supplied to one coil or set of coils and the magnetic flux set up in the iron core and around the coil induces currents in the second set of coils, the voltage across these coils being either higher (step up) or lower (step down) than the voltage supplied.

The coil to which power is fed is known as the primary and those from which power is taken as secondaries.

The number of turns of each coil of the transformer varies inversely as the size of the core.

Why Laminated Cores are used:-

The rapidly varying magnetic flux will induce currents in the core as well as in the windings around it and if the core were one mass of metal with a very low resistance, the current so induced would be very high. This current represents a waste of electrical energy which serves only to heat up the core. This current is known as "eddy current" after the name of the scientist who discovered it. In order

to reduce the eddy currents to a negligible value, the electrical resistance of the core is increased by splitting it to thin sheets and insulating each sheet from the next. Eddy currents will still flow but the total loss of power so caused will be far less than otherwise it would be because the currents in the laminated sheets are divided down into very narrow areas.

Laminations are insulated from one another in many ways : by chemical treatment of the metal surface, by varnish, by thin cemented paper etc.

There are two main shapes of laminations : (1) the E and I type and (2) the T and U Type. Both types form a three legged core

Calculations

The cross sectional area of the core is chosen from the formula:

(1) $A = \frac{\sqrt{W}}{5.58}$ where W is the power output of the transformer in Volt-amperes (VA) and A is the cross section area in square inches.

Squaring and transposing equation (1) we have

(2) $W = (5.58)^2 A^2 = 51.13 A^2$ where all the letters have the same meanings as in eq (1)......(2)

Equation (2) represents the maximum power that can be handled by a transformer of a given cross sectional area.

(3) Having determined the cross sectional area and the maximum power handling capability of a power transformer. we have to ascertain its "Number of turns per volt" denoted by N. (Note that here N does not denote the Transformation Ratio)

Turns per volt indicates the voltage carried by every loop of a transformer. It is calculated as follows.

$$N = \frac{10^8}{4.4 \times FXHXA} \quad \text{.......} \quad (4)$$

N is number of turns per volt.

F is the frequency in HZ of the applied EMF

H is the maximum number of lines of magnetic flux per square inch of the core and A is cross-sectional are a of the core.

Example : A power transformer is to be designed with the following specifications:

Primary = 200 V

Secondaries (i) 350 V at 120 ma

(li) 6.3 V at 3A

(iii) 5 V at 2.2 A

Solution

Step 1 : Find the total output wattage thus :-

(i)	350 × 120 mA	= 42 watts	
(ii)	6.3 × 3A	= 18.9 "	
(iii)	5 × 2 2 A	= 11 "	
	Total	71.9 "	

Step 2 : Find the cross-sectional area of the core

$$A = \frac{\sqrt{72}}{5.88} = 1.5 \text{ Sq in (From EQ 1)}$$

We give a safety margin of .3 Sq in and make A = 1.8 Sq in

Step 3 : Find the input wattage thus.

Assume the transformer to be 90% efficient (which is normally the case)

The output wattage is 72 watts

$$\text{Input wattage} = \frac{72 \times 100}{90} = 80 \text{ watts}$$

Step 4 : Find the primary current thus:-

At the working voltage of 200 V, the primary will take

$$\frac{80}{200} = .4 \text{ Amps.}$$

The wire of the primary must be chosen so as to carry this current safely.

Precaution : Care must be taken to ensure that the enamel coating of the wire does not get cracked, kinked or rubbed: a breakdown in insulation in a single winding renders the whole transformer useless.

The best type of wire to use in the primary circuit is enamelled wire with the added protection of a single silk covering

Step 5 : Find N, the number of turns per volt from eq 4, thus :

The frequency of the applied EMF is taken as 50 HZ

H the flux density, is taken as 60,000 lines per sq inch which is the commonly accepted value of it.

A is taken as 1.8 Sq in from Step 2

$$N = \frac{10^8}{4.44 \times 50 \times 60{,}000 \times 1.8}$$

$$= \frac{1}{124} \text{ or 4.2 turns per volt}$$

Step 6 : The number of turns of the windings can now be found thus :
Primary ; $200 \times 4.2 = 840$ turns (there are 4.2 turns per volt — Step 5)

Secondaries : (i) $350 \times 4.2 = 1050$ turns
(ii) $6.3 \times 4.2 = 26.5$ turns
(iii) $5 \times 4.2 = 21$ turns

Step 7 : To find the wire guages.

For this type of transformer, it is safe to choose the guages on the basis of a current flow of 2000 amps per square inch, i.e. the readings under the relevent column of SWG Table should be multiplied by 2 or the current rating of the windings should be halved.

Thus, the primary current is .4 amp (Step 4). To find the SWG we should find out the reading of .2 under the relevant column 14.

Primary should be wound with 27 SWG enamel and single silk covering.

Secondaries :

(a) HT 350 V winding carries 120 mA. Half of it is .06 amps. Therefore, find out a reading of .06 from the Table IV. Notice that SWG 33 and SWG 34 both will meet the requirement.

(4) Heater windings : take 2 to 3 amps. Half of it is 1 to 1.5 amps. SWG 18 wire will meet these requirements adequately.

To summarise, therefore,

Primary winding : 26 SWG 840 turns.

Secondary windings :

HT = 34 SWG 1050 turns
Heaters = 18 SWG : (a) 26.5 turns
(b) 21 turns

Step 8 : Constructional details

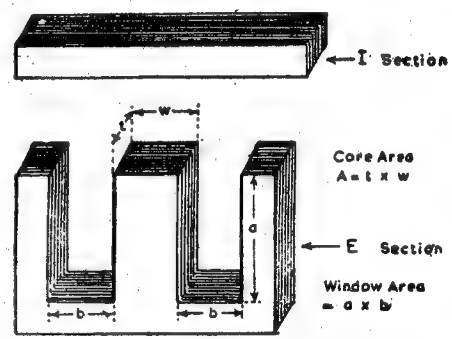


Fig. 3 Core Dimensions and Winding Area.

The windings are made on a former which is a tube that will fit the core tightly with end cheeks to clear the "Window space" and through which the leads will pass. Such a former can be home-made out of stiff card board or paxolin which should be well coated with shellac.

The tube is first made to fit the core and the end cheeks are fitted; then the entire assembly is well varnished and allowed to become hard

The "window space" is the size a × b shown in the dimensions are given as $1\frac{1}{8}'' \times 1\frac{7}{8}''$

The former generally will be made of 1/8" card board or paxolin Thus after fitting the former, the dimensions of the "window" will be reduced i.e. its depth will become 1" and its length will become $1^5/_8$" (since 1/8" will be reduced from both ends off $1\frac{7}{8}$"

Now we can calculate the space which will be taken by each winding.

Primary SWG 26 enamel and silk wind 48 turns per inch.

The former will take 48 × $1\frac{5}{8}$ turns per layer or 78 turns.
The number of layers will be 840/78 or 10.7 layers.
The height of the winding will be 10/48 = .2" approx
HT Secondary : SWG 34 enamel wire will wind 100 turns per inch so that each layer will have 100 × $1\frac{5}{8}$ = 162 turns
The number of layers will be 1050/162 = 6 approx.
The height of the winding will be 6/100 = .06"

Low Voltage Secondaries : SWG 18 enamel wire winds 19.7 turns per inch so that one layer will contain 19.7 × $1\frac{5}{8}$ = 32 turns. Thus, both the low voltage windings will be easily accommodated into one layer.

Having considered how to calculate the various parameters of a power transformer we shall now give a few major guidelines for its construction.

(a) The primary is always wound first. The terminals of the wire which are to be soldered are cleaned with spirit, not by scraping. They are soldered to flexible leads. Take care that the soldered joint is perfectly smooth with no sharp points or projecting wire ends. The flexible leads are then covered with insulating sleeve through the cheek.

(b) The tap for the various primary voltages can be taken out in the same manner as the taps on the coils mentioned earlier.

A loop of wire is drawn out and returned to the next turn without any breaks or joints.

(c) When the primary winding is completed, it must be insulated from the subsequent coils.

(d) The HT winding is then taken up, taking the precautions of not damaging the insulation at any point of the windings.

(e) When the former is wound, it is given a covering of cloth. Then the laminations are inserted into the centre aperture, so that they are alternated i.e. one E must go in from the left with an I from the right; then an I from the left and an E from the right and so on, the laminations being brought into tight contact with no air gaps.

The stampings must be inserted carefully for it may be possible to run a sharp edge or corner into and through the former material, cutting or scraping the primary winding.

The laminations must be clamped into a solid mass with wooden or metal clamps which can be drilled to provide fixing holes for bolting the transformer to chassis.

EHT Transformers.

It is unlikely that a hobbyist will undertake the task of winding an EHT transformer used in Television sets. However, two general points are given here for guidance.

1. The peak inverse voltage across such a transformer might reach as high 10,000 volts.

2. At high voltages a trace of moisture upon an insulating surface might give rise to sparking or arching. which, while slight at first would rapidly short circuit the windings. For this reason the layers of the secondary are not carried to the end cheeks of the former and as the winding grows outward from the centre, the layers are made shorter, giving a pyramidical shape. In this way, as the potential above earth rises through the windings, so does the distance between any earthed object and the increase in winding.

Filter Chokes.

Chokes are inductors which are employed in electronic circuits for two purposes (1) smooth out ripples after rectification of the AC voltages and (2) couple one stage to another. In either case they are distinguished from other coils and transformers considered earlier by the fact that they have to carry a substantial value of DC current in addition to AC.

The value of the inductance required for a particular choke is determined by the impedance which it will have at a certain fre-

quency. For smoothing, this frequency is that of the ripple to be eliminated in smoothing, and for coupling chokes, it is the lowest frequency required to be passed on to the next stage. As we have noted earlier the reactance of an inductor (XL) is given by.

$XL = 6.28 \times f L$ where f is the applied frequency in HZ and L is its inductance in Henries.

Smoothing Chokes:

For a smoothing circuit the value of the capacitor also must be known and is given by

$$XC = \frac{10^6}{6.28 \times f \times C}$$ where f is the applied

frequency in HZ and C is the capacitance of the capacitor in micro farads (uf)

Smoothing factor : If a smoothing circuit is required to reduce the ripple voltage to a certain fraction of that existing across the reservoir condenser, then the required ratio of the reactance of the smoothing condenser to that of the choke is known as the smoothing factor. For example

if, the ripple voltage is to be reduced by $\frac{1}{40}$, then

$$\frac{XC}{XL} = \frac{1}{40} \qquad \text{EQ 1}$$

Let the value of the smoothing capacitor be 8 uf. Its reactance to a ripple voltage of 100 HZ (the ripple frequency obtained from a 50 HZ full wave rectifier) will be

$$\frac{10^6}{6.28 \times 100 \times 8} = 200 \text{ ohms approx}$$

Therefore, the reactance of the choke

$$XL = 40 \times 200 = 8000$$

$$L = \frac{8000}{6.28 \times 100} = 13 \text{ Henries approx}$$

Coupling Chokes : In ascertaining the inductance of such chokes two factors have to be taken into account : (a) the lowest frequency which is required to be reproduced and (b) the impedance which the choke has to match with the impedance of the active element (tube or transistor). The following formula is used.

$$L = \frac{\text{Impedance in ohms of the active element}}{6.28 \times f}$$ where f is the

lowest frequency to be reproduced and is the inductance in henries

Allowances : While calculating the inductance values of the smoothing and coupling chokes given in the foregoing paragraphs, 15% and 20% of the calculated values of inductance are added in the cases of smoothing and coupling chokes respectively due to following factors:

(1) there is always a certain amount of of DC flowing in these chokes, thus reducing the effective value of the inductance (Core saturation effect) (2) Changes in mains voltages also reduce the effective value of the inductance of the choke. and (3) voltage drop across the choke:

Due to the dc flow through choke, some amount of voltage is dropped across it. Provision must be made so that the choke shall not drop more then a certain DC voltage across it due to its dc resistance.

The above three factors determine how large the choke must be physically.

AIR GAP : The effect of DC in saturating the iron core of the choke is offset by inserting an air gap in the core. This is analogous to inserting a resistance in the dc electrical circuit.

The size of air gap in the core depends upon the ampere-turns of the choke i.e. the value of the DC current which the choke has to carry multiplied by the number of turns of the choke. Higher the ampere turns, larger is the size of the air gap required to eliminate core saturation effects. Usually the size of the air gap varies from .001" to .035".

Remember both a large air gap and a very small air gap reduce the effective inductance of the choke,-the former by allowing a large number of magnetic lines of force escaping through the air gap instead of cutting the adjacent turns of the winding wire; the latter by opposing the formation of the requisite number of magnetic lines of force when AC current is passed through the choke windings.

TABLE III

WAVELENGTH—FREQUENCY CONVERSION METRES TO KILOHERTZ READY RECKONER

Meters	KHZ	Meters	KHZ	Meters	KHZ
5	60000	300	1000	590	508.5
6	50000	310	967.5	600	500
7	42857	320	937.5	650	461.5
8	37500	330	909.1	700	428.6
9	33333	340	882.3	750	400
10	30000	350	857.1	800	375
25	12000	360	833.3	850	352.9
50	6000	370	810.8	900	333.3
100	3000	380	789.5	950	315.9
150	2000	390	769.2	1000	300
200	1500	400	750		
205	1463	410	731.7		
210	1429	420	714.3		
215	1395	430	697.7		
220	1364	440	618.8		
225	1333	450	666.7		
230	1304	460	652.2		
235	1277	470	638.3		
240	1250	480	625		
245	1225	490	612.2		
250	1200	500	600		
255	1177	510	588.2		
260	1154	520	567.9		
265	1132	530	566		
270	1111	540	555.6		
275	1091	550	545.4		
280	1071	560	535.7		
290	1034	570	526.3		
295	1017	580	517.2		

TABLE-IV

SWG No.	Dia in inch	Ohms per 1000 Yds	Enamel	Turns Per inch close wound: Single Silk	Double Silk	Single Cotton	Double Cotton	Enamel	Turns per sq. inch: Single Silk	Double Silk	Single Cotton	Double Cotton	Current at 1000 Amps per SQ inch	Sectional Area of wire in Sq. inch	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1	.30	.33											71	.07	
2	.27	.40											60	.06	
3	.25	.48											50	.05	
4	.23	.56											42	.04	
5	.21	.68											35	.03	
6	.19	.82											29	.028	
7	.17	.98											24	.024	
8	.16	1.1											20	.02	
9	.14	1.4											16	.016	
10	.12	1.8	8			7	7	58				49	13	.013	
11	.11	2.2	8.3			8	8	69				59	11	.01	
12	.10	2.8	9			9	9	86				72	9	.008	
13	.09	3.6	10			10	10	108				89	7	.007	
14	.08	4.7	12			11	11	141					113	5	.005
15	.07	5.8	13			13	12	175					141	4	.0047
16	.06	6.6	15	15	15	14	13	219	216	210	193		169	3	.003
17	.05	9.7	17	17	17	16	15	265	279	272	246		216	2	.0025
18	.048	13.2	20	20	20	18	17	388	392	376	324		285	1.8	.002
19	.04	19.1	24	24	23	21	20	550	552	529	441		384	1.3	.0013
20	.036	23.5	26	26	26	24	21	676	676	640	552		451	1	.001
21	.034	29.8	29	29	29	27	23	852	847	800	681		540	.8	.0008
22	.028	38.9	33	33	32	29	26	1089	1089	1017	846		655	.6	.0006
23	.024	53	38	39	37	35	29	1513	1568	1350	1169		860	.5	.0005
24	.022	63.1	42	43	40	37	31	1789	1800	1590	1346		971	.4	.0004
25	.02	76.4	47	47	44	40	33	2070	2160	1860	1568		1105	.3	.0003
26	.018	94.3	52	52	49	44	36	2650	2600	2300	1850		1270	.25	.00025
27	.017	114	57	57	53	47	38	3190	3170	2750	2100		1430	.21	.0002
28	.015	140	63	62	58	51	40	3900	3800	3300	2500		1620	.17	.00017
29	.013	165	68	67	62	54	42	4550	4450	3800	2800		1790	.15	.00014
30	.012	199	75	73	67	58	45	5550	5300	4450	3250		1980	.12	.00012
31	.011	227	79	78	71	60	46	6300	6000	5000	3550		2140	.1	.00011
32	.0.08	262	86	83	75	63	48	7300	6800	5600	3950		2340	.09	.00009
33	.01	306	92	89	80	67	50	8400	7800	6400	4350		2500	.07	.00008
34	.009	361	100	95	86	70	52	10000	9000	7300	4850		2700	.06	.00007
35	.008	433	109	103	92	81	58	12000	10000	8400	6400		3300	.05	.00006
36	.007	529	120	112	99	86	60	14500	12500	9750	7370		3600	.04	.00005

Table 4 (contd. on page 50)

Table 4 (contd. from page 49)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
37	.0068	661	135	123	107	99	63	18200	15000	11000	9650	4000	.03	.00004
38	.006	849	151	137	118	100	67	22900	18500	13500	9900	4400	.028	.00003
39	.005	1130	175	154	130	109	70	30600	23500	16500	11500	4900	.021	.00002
40	.0048	1327	189	164	137	114	72	35600	26500	18500	12600	5200	.018	.000018
41	.0044	1579	208	179	151			43000	32000	22000			.015	.000015
42	.004	1911	227	192	161			51000	36500	25500			.012	.000012
43	.0036	2359	256	208	172			65000	43000	29000			.01	.00001
44	.0032	2985	285	227	185			81000	51200	34000			.008	
45	.0028	3899	322	250	200			104000	62000	39500			.006	
46	.0024	5307	377	278	217			142000	72000	46500			.004	
47	.002	7642	444	312	238			197000	97000	56000			.003	
48	.0016	11941											.002	
49	.0012	21230											.001	
50	.001	30570											.0007	

Table V (See EQ 13)

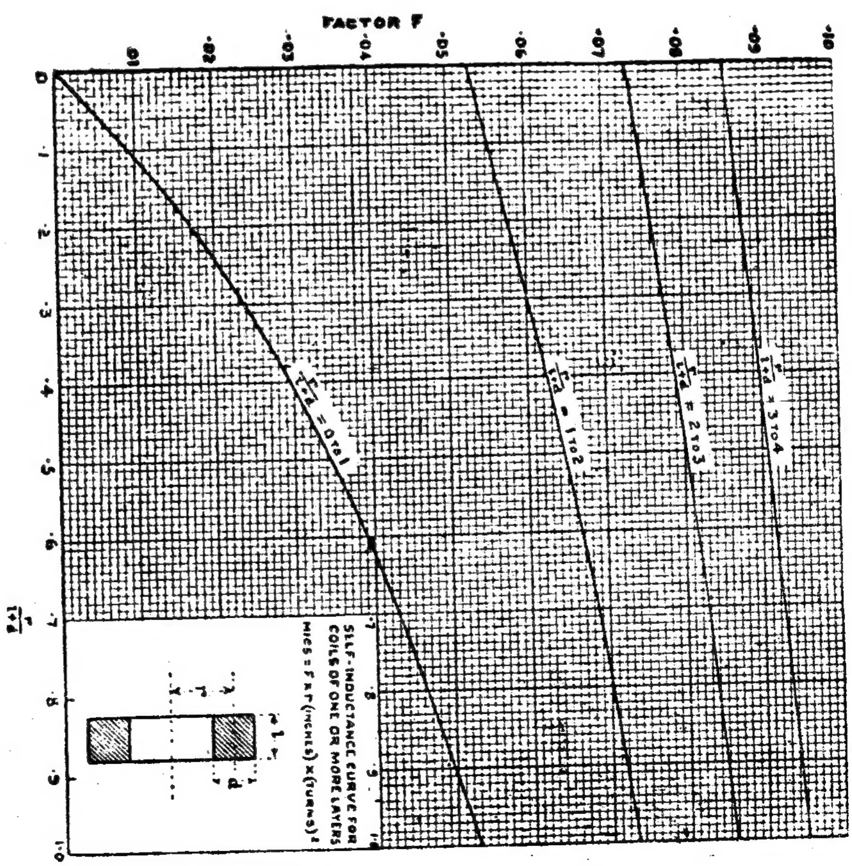
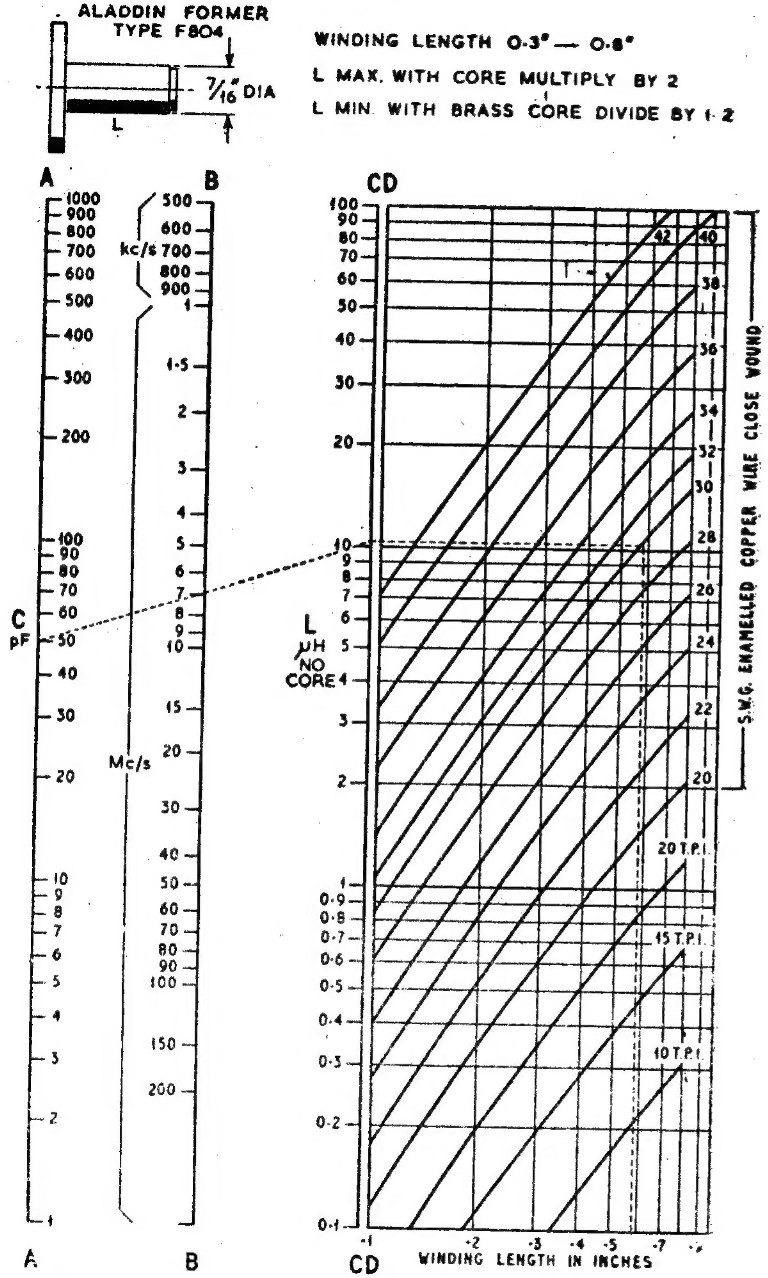
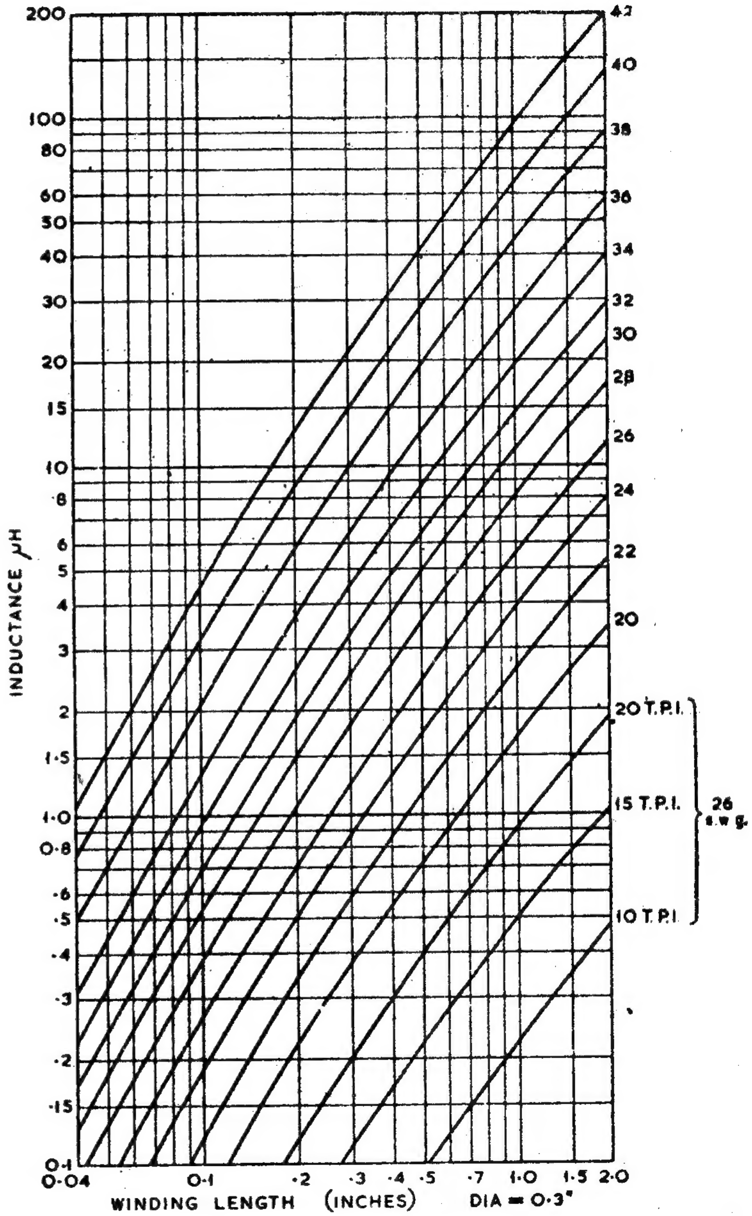


Table VI



The calculation of inductance required and winding data

Table VII



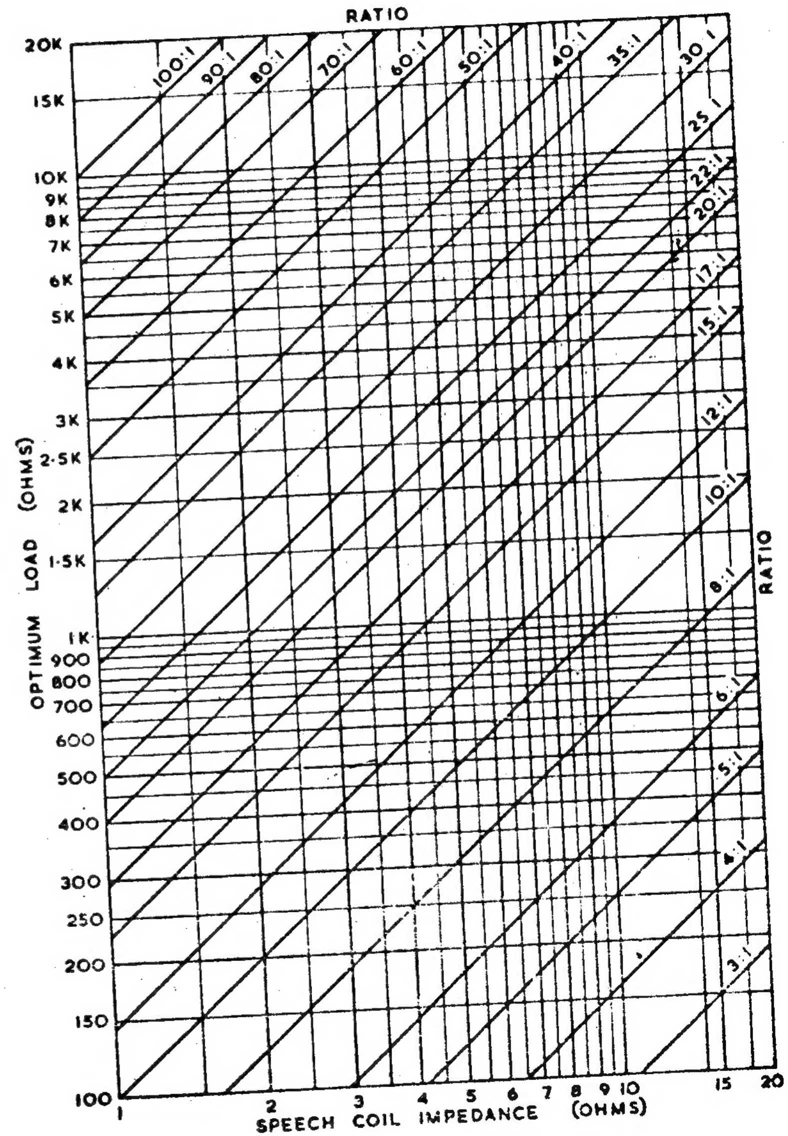
Winding data for 0 3 in. diameter coil forms.

TABLE VIII

Impedance/Turns Relationship : Audio Frequency Transformers/chokes

Length of Winding	Thickness of Winding	Number of Turns for 1000 ohms impedance	Mid-Band Losses	Low Frequency Cutt-off in Cycles
¾"	¾"	750	11.5%	90
	1⅛"	660	10 %	90
	1½"	500	9.3%	70
1"	1"	770	8.5%	65
	1½"	670	7.4%	60
	2"	500	6.8%	55
1¼"	1¼"	790	6. %	53
	1¾"	700	5.4%	46
	2½"	620	4.8%	43
1½"	1½"	800	4.8%	39
	2¼"	720	4.3%	35
	3"	640	4. %	32

Table IX



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